Measuring Mercury

Mercury is ubiquitous in the environment. Spewing from volcanoes, evaporating off bodies of water, and rising as gas from the Earth's crust, the poisonous, metallic element floats in the air as vapor or binds to particles. Eventually it falls to the Earth to settle in sediment, oceans, and lakes, or reenters the atmosphere by evaporation. The "hand of man" has contributed to this outpouring as well. Since the late 18th century and the dawn of the Industrial Revolution, mercury has been used in products such as lightbulbs, batteries, thermometers and barometers, pesticides, and paint. It is released from the burning of fossil fuels in municipal and hospital incinerators, coal combusting powerplants, lead smelters, and chlorine producers. Because it can dissolve metals, and particularly because it can separate gold from impurities, it has long been used heavily in mining, and is found in tailings around the world. Even crematoria contribute mercury to the environment as mercury is released when dental amalgams melt.

Element of destruction. Mercury from natural and man-made sources is released into air, soil, and water. Bacteria convert mercury to methylmercury, which accumulates in fish that are eaten by humans and may cause adverse health effects.

Once in water, mercury accumulates in fish. As a result, the consumption of fish becomes the primary pathway by which humans are exposed to methylmercury (another form of mercury). At elevated levels, poisoning can occur. Fetuses are particularly at risk and can suffer damage to the central nervous system, mental retardation, and a lack of physical development as a result of mercury exposure. Effects on adults can also be severe and include both sensory and motor skills damage.

Because it cuts across both environmental and public health concerns, two federal agencies with two different (though often overlapping) mandates—the EPA must safeguard human health through protecting the environment, while the FDA must safeguard human health through regulation of foods and drugs—have responsibility for regulating exposure to methylmercury. Right now, the agencies disagree on how best to fulfill these mandates and set standards for safe levels of methylmercury as they continue to examine the same data from two different perspectives. How the issue will be resolved is not clear, but interested parties, including industry and fishing lobbyists, consumer groups, and environmentalists, are working to influence the decisions of the two agencies.

Where and How Much

The World Health Organization estimates that approximately 10,000 tons of mercury are released worldwide from both natural and manmade sources each year. Initially, it floats into the atmosphere, mostly in the form of mercury vapor (Hg). Eventually, rainwater washes it back down to the Earth, where the process is repeated in what is described as a "ping-pong" effect. "As with any of the chemical elements, mercury exists as part of the Earth," says Kathryn Mahaffey, a senior scientist with the EPA. "As an element, it's not going to be created or destroyed, but its chemical form can always change." Over time, the ultimate sink for mercury is in the sediments of the Earth's oceans and lakes. There, microorganisms convert the inorganic mercury to methylmercury, the form that is potentially harmful to humans.

Methylmercury is produced by methanogenic (TK) bacteria (that produce methane), some of the oldest living cells known, says Tom Clarkson, a toxicologist at the University of Rochester. When mercury is methylated through ingestion by microorganisms, a carbon atom is added on to the mercury atom. This additional atom is what changes mercury's properties, allowing it to be readily accumulated in fish.

Exactly why the microorganisms methylate mercury isn't clear, says Clarkson. "Generally, inorganic mercury is more toxic to the organism, so it may be they convert it to get rid of it." Once it's methylated, mercury leaves the microorganism and moves up the aquatic food chain. "So what's good for them," says Clarkson, "becomes bad for us."

Once released from microorganisms, methylmercury rapidly diffuses, binding to proteins in aquatic biota. From there it marches up the food chain in a process known as biomagnification. Simply put, smaller fish absorb the methylmercury from water as it passes over their gills and as they feed on methylmercury-tainted flora and fauna. In turn, these fish are eaten by bigger fish, which is why the highest concentrations of methylmercury are found in fish at the top of the aquatic food chain. Large, predatory species like tuna, swordfish, and shark in ocean waters and trout, pike, walleye, and bass in fresh waters contain more methylmercury in their tissues than smaller, nonpredatory fish. Also, the older the fish, the more time methylmercury has to accumulate.

The transference of mercury from emissions to fish is nothing new. "Methylmercury has probably been in fish as long as fish have been on this planet," notes Clarkson. What is new is that people are eating more fish; in 1992 it was estimated that in today's supposedly more health conscious United States, fish consumption has risen 25% in the last ten years as people seek to benefit from fish's high protein and low unsaturated fatty acids, calories, and cholesterol, all of which may prevent heart disease and have other beneficial health consequences.

But scientists say that eating too much fish may have adverse impacts on health because of the increased intake of highly toxic methylmercury. "No one is arguing whether or not there are neurobehavorial effects of mercury on children exposed *in utero*," says Mahaffey. "Mercury is one of the most firmly established neurotoxins there is." If exposed in the womb, children can later develop a whole host of problems, ranging from delays in speech or walking to severe brain damage. FDA officials stress, however, that these effects have only been seen in populations exposed to high levels of methylmercury.

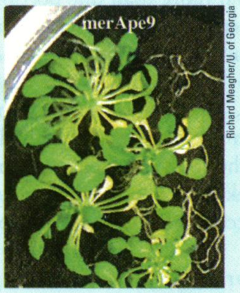
"It came as a shock to us in 1969 when Swedish scientists first discovered that methylmercury could accumulate in fish," says Clarkson. "In fact, there was a near-panic among people when high levels were found in fish near Detroit. People thought they were going to be poisoned." This good fish–bad fish conundrum is what the FDA and EPA are trying to resolve. "We've been wrestling with this issue for some time now," says Michael Bolger, a toxicologist and chief of the contaminants section for the FDA.

FDA Advisories

In 1979, the FDA established an "action level" of 1.0 part per million (ppm) to regulate methylmercury in commercial fish. The level serves a two-fold purpose. As the agency that oversees the safety of commercial fish in interstate commerce, the FDA uses this measure to make recommendations for legal action when a sample of the fish in a given shipment contains levels of methylmercury in excess of 1.0 ppm in the edible portion. This level is also used to assess risk to human health. As part of their normal diet, 1.0 ppm is the maximum level of methylmercury in fish that humans

Removing Mercury

The best way to remove mercury pollution from soil may one day be simply to grow plants in it. In a study published in the 16 April 1996 issue of the *Proceedings of the National Academy of Sciences*, researchers at the University of Georgia announced that they had developed a plant capable of absorbing highly toxic mercury ions from a growth medium and reducing them to less toxic and relatively inert metallic mercury. Once converted to its metallic state, the mercury is transferred into the atmosphere as a vapor.



Toxic fertilizer. *Arapidopsis* plants expressing the *merApe9* transgene are capable of absorbing toxic mercury ions.

According to the report, the scientists developed the mercury-eating plant by building a synthetic gene, *merApe9*, and inserting it into the genome of *Arabidopsis*, a mustard plant. The *merApe9* sequence, which is an adaptation of a bacterial gene, encodes the production of mercuric ion reductase.

The viability of phytoremediation, the process of using plants to remove pollutants from the environment, has been shown for many chemicals. Pesticides, herbicides, explosives, solvents, radioactive cesium and strontium, and other heavy metals such as nickel and lead have all been shown in various studies to be potential candidates for phytoremediation cleanup. "The significance of this study," says Ilya Raskin, a professor of plant biology at Rutgers University, "is that it is the first one published . . . [that] demonstrates the potential of genetic engineering for developing plants" capable of absorbing particular chemicals. According to a paper by Raskin that accompanied the study, this research could lead to the development of "a 'molecular toolbox' of genes useful for phytoremediation of metals."

The study also shows that mercury pollution is particularly suited for cleanup using phytoremediation. With most chemicals, the plants that grow on the contaminated medium accumulate large amounts of the toxic substance into their biomass, which must then be disposed of. According to Raskin, substantial savings are still achieved in these cases because the plant biomass represents around 1000 times less toxic material to be disposed of than the soil in which it was grown. However, because of mercury's volatility, it does not accumulate in the plants. According to the study, metallic mercury vapor was emitted by the plants as they grew; the researchers propose that, outdoors, this vapor would diffuse into the atmosphere, quickly reaching nontoxic levels.

According to Raskin, though, regulatory agencies may not accept the evolution of metallic mercury into the air as a safe remediation strategy. In particular, there is concern that mercury vapor in the air will precipitate into the Earth's waters where it can enter aquatic food chains. Through the process of biomagnification, this mercury can reach toxic levels in the predatory fish that humans consume. According to Richard Meagher, one of the authors of the study, however, the mercury vapor released during a phytoremediation cleanup would be insignificant on a global scale. "The amount of vapor coming out of a site will be 10,000-fold less than EPA [emissions] standards," Meagher said.

However, Raskin stresses that phytoremediation of mercury is still in its infancy, and that much more research is needed. "The next step," he said, "clearly is to introduce these genes into high biomass plants and show that it works on soil." Though some phytoremediation schemes have been field-tested, mercury-removing plants have only been grown on agar under laboratory conditions, Raskin said. In addition, *Arabidopsis*, a common test plant, does not reduce enough mercury and lacks the field cultivation to make it a practical choice for phytoremediation cleanup. "This study is just one step, but it's a very significant one," he said.

Chris Reuther

should eat on a frequent and consistent basis, but Bolger adds that such a number by itself is not helpful without taking other factors into consideration, such as how much fish people eat and what particular species they consume. "There's a problem with having a single number for a heterogeneous food like fish," says Bolger, "because unlike beef and poultry, which are consumed in fairly consistent amounts, there are pronounced differences between what species of fish are consumed, in what amounts, and how often. Looking at a single, safe level in a fish doesn't tell you anything about how much and how often that fish is consumed."

For instance, swordfish and shark, two big fish that are high up on the food chain, have methylmercury levels over 1.0 ppm. Yet most people eat these two fish on an occasional basis only. Thus, the FDA states that swordfish and shark "are safe, provided they are eaten infrequently (no more than once a week) as part of a balanced diet." Another complication is that levels of methylmercury vary between species. Canned tuna, for example, the number-one consumed fish in the United States, has fairly low levels of mercury—about 0.2 ppm, says Bolger. But certain species of very large tuna, which are not used in canned tuna but are typically sold as fresh steaks or sushi, can have levels over 1.0 ppm. Again, though, most people only eat tuna steak infrequently, so an occasional meal of it is probably okay.

Still other differences depend on who's doing the eating. Due to the fact that fetuses are especially vulnerable to methylmercury's effects, the appropriate levels for women of child-bearing age to consume may not be the same as for other people. In the womb, says Bolger, humans are susceptible to the effects of high methylmercury exposure because of the sensitivity of the developing nervous system. "Methylmercury easily crosses the placental barrier," he says. What the FDA didn't know when the action level was established, and still doesn't know, is the effect on the fetus of "normal" methylmercury exposures seen with fish consumption. The question, Bolger says, is whether effects on fetuses can occur with levels of exposure lower than those associated with adverse effects on adults seen in poisoning episodes.

To allow for such variation, the FDA has issued suggested guidelines for eating fish. FDA consumer literature states that eating a variety of types of fish does not put anyone in danger of methylmercury poisoning. Pregnant women and women of child-bearing age, though, are advised by the FDA to limit their consumption of shark and swordfish to no more than one portion a month. The literature also says that for persons other than pregnant women and women of child-bearing age who may become pregnant, regular consumption of fish species with methylmercury levels around 1.0 ppm should be limited to about 7 ounces per week (about one serving) to stay below the acceptable daily intake for methylmercury.

Part of the problem in establishing guidelines has been the lack of good data. To arrive at their current action level, the FDA looked at data from several studies of methylmercury poisoning and at the amount of fish consumed by the U.S. population—the best available data at the time. Two of the worst poisoning incidents occurred in Minamata and Niigata, Japan. In the 1950s, 111 people died or suffered from nervous system damage in Minamata, while 120 people were poisoned in Niigata. Both incidents were caused when people ate fish—often daily over extended periods—from waters that were severely polluted with mercury from local industrial discharge. In particular, 23 children in Minamata had severe psychomotor retardation resulting from their mothers' eating contaminated fish while pregnant. Yet the mothers themselves showed only mild manifestations of poisoning or no damage at all.

The studies also showed that harm caused by methylmercury poisoning, particularly neurological symptoms, can progress over a period of years after exposure has ended. The average methylmercury content of fish samples from both areas ranged from 9.0 to 24 ppm, although in Minamata, some fish had levels as high as 40 ppm. Because methylmercury accumulates in the hair of exposed individuals, its concentration can be measured in newly-formed hair and is proportional to the concentration of methylmercury in the blood. Although methylmercury levels in the Minamata mothers were not recorded, toxicologists learned that the lowest methylmercury level in adults associated with toxic effects was 50 ppm in hair. By comparison, the average concentrations of total methylmercury in nonexposed people, according to the FDA, is about 2.0 ppm in hair. "Obviously, these children were grossly compromised," says Bolger, "but those were at levels of exposure that were much higher than the lower dosages associated with minimal effects in adults."

More confusion and controversy arose regarding the potential danger to fetuses with the publication of a study in the mid-1980s led by Clarkson. In the study, based on 81 infant–mother pairs, Clarkson investigated an outbreak of poisoning in Iraq that occurred in the early 1970s when seed grain that had been treated with a methylmercury fungicide was ingested. "The interesting thing we found in Iraq," says Clarkson, "was that the level of methylmercury we found in the mother was predicative of adverse effects in their offspring. We looked at kids about two to two-and-a-half years old and found certain neurological effects, delayed development,

Mercury Timeline

1953
111 people die or suffer nervous system damage in Minamata, Japan from eating fish from waters severely polluted by mercury from industrial discharges.

1965
120 people are poisoned in Niigata, Japan from eating fish polluted by methylmercury.

1969
Swedish researchers discover that methylmercury accumulates in fish.

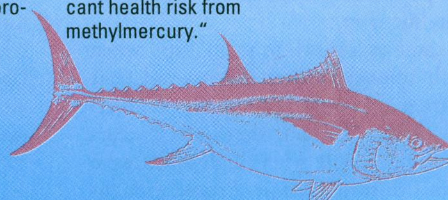
1969
The FDA sets a 0.5 part per million (ppm) action level as the maximum safe limit for total mercury in fish. Action levels are the limit at or above which the FDA will act to remove a product from the market.

1971-1972
A methylmercury poisoning outbreak occurs in Iraq when seed grain treated with a methylmercury fungicide is ingested. Children born to mothers who were pregnant at the time they ate the grain were found to have neurological effects, delayed development, and delayed motor skills.

1979
The FDA raises the mercury action level to 1 ppm based, in part, on a National Marine Fisheries Service study that showed this level would adequately protect consumers.

1980
The World Health Organization publishes a study on methylmercury toxicity that states that "the general population does not face a significant health risk from methylmercury."

1984
The FDA changes the basis for enforcement of the mercury action level from total mercury to methylmercury.



and delayed motor effects. It was the first time anybody had shown this."

From the analysis, says Clarkson, estimates were made that levels of methylmercury in the mother's hair that were somewhere between 10 and 20 ppm were associated with roughly a 5% risk of adverse effects in her offspring.

But there were several problems with the study. One was a significant uncertainty in the estimates due to the low numbers of people in the study. Clarkson was also concerned about whether the results could be applied to a fish-eating population in the United States—"After all, people living in the middle of a desert weren't eating fish," he notes—and the fact that the Iraqi poisoning came from contaminated bread, not fish. He then decided to conduct another study, one of a primarily fish-eating population.

Conducting such a study was easier said than done. It took Clarkson more than two years of literally searching the world until in 1980, he found the right population in terms of size and birth rate (among other factors), in the Seychelle Islands in the Indian Ocean. "We needed a birthrate of 1,000 a year; that would give us the 800 infant–mother pairs we needed to check the 5% risk factor from Iraq," Clarkson said. Clarkson and colleagues followed two groups in the Seychelles in an initial pilot study that examined about 750 children up to five-and-a-half years old, followed by a main longitudinal study of 740 children nearly two-and-a-half years old. Both studies evaluated mental and physical development.

Initial results, reported in the Winter 1995–1996 issue of *Neurotoxicology*, were positive. "We weren't able to find major health problems," says Clarkson. "Children seemed to be developing normally, and in the tests done so far, the children were meeting the usual developmental milestones." According to Clarkson, the Seychelle results show that the predictions from Iraq, based on the estimates of adverse effects at 10–20 ppm exposure, are not true. Says Clarkson, "That's interesting, but not too surprising. Bear in mind that [the Iraq] numbers had a lot of uncertainty in them. They could have been as high as 70 ppm. What we're looking at right now is the exposure of the mother during pregnancy and the delayed effects on the child. . . . Suppose the child's brain was somehow damaged during pregnancy; it might be several years before you'd see the results of that. That's why we plan to follow the children until they're six to seven years old or more."

Philip Davidson, a University of Rochester psychologist and Clarkson's colleague on the Seychelles study, also presented additional analysis of the relationship of maternal mercury levels to activity scores in infants at 29 months of age. The original finding, reported in the Winter 1995–1996 issue of *Neurotoxicology*, showed a correlation between decreasing activity scores and increasing maternal mercury levels. A further analysis revealed that decreased activity was primarily associated with male children of mothers having lower scores on a test of maternal intelligence. Says Clarkson, "We do not know how to interpret a decreased activity level. In studies of childhood exposure to lead, increased activity (hyperactivity) was interpreted as an adverse effect of lead." Clarkson stressed that these findings are preliminary and their health significance is not known. Furthermore, these effects were observed in a population of children where all other tests indicated no problems in development.

As Clarkson's study was unfolding, a second, complementary study of a fish-eating population, led by Philippe Grandjean from Odense University in Denmark, was beginning in the Faroe Islands, located between Scotland and Iceland in the North Atlantic. Because the study results have not yet been published, Grandjean declined to talk about the findings. However, regarding a pilot study of 917 children who were examined at 7 years of age, Grandjean said, "We did see indications of neuropsychological dysfunction associated with increasing methylmercury exposure levels." Also, in a paper presented at the September 1994 National Forum on Mercury in Fish, Roberta White, a neurologist at the Boston University School of Medicine and an investigator with the Faroe Island study, wrote that the preliminary results from the first year of data collection show there is a relationship between maternal intake of seafood during pregnancy and central nervous system function in children 7 years later.

EPA Standards

In the early 1990s, the EPA had begun to prepare its own mercury study for Congress as mandated by the 1990 Clean Air Act. This report included the EPA's own assessment of an acceptable level of methylmercury in fish. Because the report was not completed by the original due date of 15 December 1993, the EPA was sued by the Sierra Club and the Natural Resources Defense Council. Although the agency was granted a one-year extension until 15 December 1994, it decided not to submit its by-then completed report. The environmental groups sued again. The EPA lost and was ordered to submit its report by 15 April 1995. It has since delayed the report yet again and, as of May 1996, was in negotiations to extend the deadline.

Ostensibly, the EPA witheld its report due to the impending arrival of the Seychelles Islands data. "The decision was made to hold the report in anticipation of data," Mahaffey said. Another key factor in the delay, though, was the widespread criticism the agency received in calling for a much stricter standard for the allowable

1984
The NIEHS and Rochester University begin a study in the Seychelles Islands, where fish is a major source of protein, to track prenatal exposure to methylmercury and effects on the fetus.

1991
Under mandate of the Clean Air Act Amendments, the EPA begins an assessment of an acceptable level of methylmercury in fish to be completed by 15 December 1993.

1992
The NIEHS and Odense University begin a study of methylmercury effects on a fish-eating population in the Faroe Islands.

1993
The Sierra Club and the Natural Resources Defense Council sue the EPA to complete and release its methylmercury report. The agency is granted a one-year extension.

1994
The EPA delays release of its report. The environmental groups sue again. The EPA is ordered to submit its report by 15 April 1995.

1995
The EPA misses the deadline for release of its report. EPA officials say the delay is due to waiting for additional data from the Seychelles studies.

1995-1996
Initial results of the Seychelles studies show no major health problems. Initial results of the Faroe Islands study, released in 1994, however, indicate neuropsychological dysfunction in children with increased methylmercury exposure levels.

1996
The EPA has yet to release its final report, although the agency has called for a stricter standard for methylmercury in fish of 0.1 micrograms per kilogram (µg/kg) of bodyweight per day.

level of methylmercury in fish—.01 micrograms per kilogram (μg/kg) of bodyweight per day. (One part per million is equivalent to 1μg/g). It is a number that the EPA says reflects its broader mandate—one that includes not only public health, but clean water and air, and the protection of fish-eating wildlife (primarily birds), who are also feeling the effects of methylmercury.

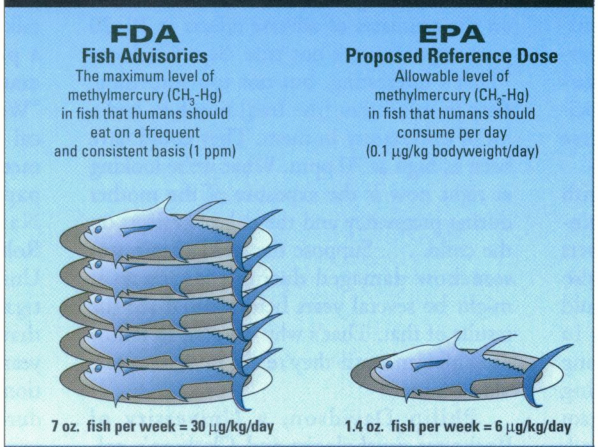
"This is really a document about the airborne sources of mercury and their impact," says Mahaffey. Besides air, the EPA is also responsible for regulating the chemical contamination of water under the Federal Water Pollution Control Act. To determine the appropriate health criteria for an allowable concentration of mercury in water, the EPA looks at human consumption of fish—again, because fish is the primary route of methylmercury exposure to humans. "What's critical to understanding our number, which we refer to as a reference dose, is that it represents a quantity of methylmercury that virtually anyone could consume over a long period of time without any adverse health effects," says Mahaffey. The EPA based its reference dose on levels that would be safe for fetuses and women of child-bearing age. That meant using the Iraqi results in their calculations, because according to Mahaffey, it was the best available data at the time. "There are various ethnic groups—people of southeast Asian descent, for example, and Native Americans—that consume more fish than the general U.S. population," says Mahaffey. "Our focus includes the average person by identifying those who would be more highly exposed. We believe if the more highly exposed people are safe then the average person will be safe too."

The number is not necessarily just for consumption of fish, Mahaffey says, but for any food that would contain methylmercury. For example, if you had methylmercury-contaminated mushrooms, the number would still be applicable. "[The reference dose] is a factor of ten lower than where we believe any effects from methylmercury would start to occur," says Mahaffey. "But we know there is population-to-population variability, that different people may respond to methylmercury at different levels. So we think that factor of ten is a way of dealing with human variability and its response to mercury."

Impacts and Implications

If adopted, the 0.1 μg/kg bodyweight reference dose could have tremendous implications for both consumers and industry. The differing measurements issued by the FDA and the EPA could be confusing for consumers. Also, they could raise a potentially embarrassing question in consumers' minds—if the EPA feels the need to drop its acceptable mercury intake levels, why hasn't the FDA—and erode public confidence in the judgments of both agencies.

Comparison of Methylmercury Standards



Note: Equivalent EPA measurement calculated based on FDA advisory of 7oz. fish per week and the World Health Organization figure of 60kg for average bodyweight.

The commercial fishing industry would presumably have to harvest fish that could meet a lower standard than the FDA's current level of 1.0 ppm. This would most likely be difficult to do. "Unlike cattle or chickens," notes the FDA's Bolger, "most fish are raised in the wild—the ocean. So it's virtually impossible to control their diet." Should demand exceed supply, fish could be more expensive or unavailable, thus depriving the consumer of the dietary advantages of fish.

There may also be a potentially huge financial impact upon those industries that emit mercury into the air. "We are of the view that there is a plausible link between these industrial sources and the quantities of methylmercury being found in fish," says Mahaffey. In order to reduce the amounts of methylmercury in fish, then, ultimately the EPA must reduce the amounts of methylmercury being emitted into the air. "Right now, pollution standards are based on existing technology," says EPA scientist Martha Keating. "If standards become risk driven, that's a whole new ballgame." More money would have to be spent by industries for research, and presumably for more expensive controls.

But to what end, asks Leonard Levin, manager for exposure and risk analysis, at the Electrical Power Research Institute, which is funded by a consortium of electric utilities. "Even if every industry that emits mercury were closed down tomorrow, it could be decades before we'd see a reduction in mercury levels in fish," he says. This is because large amounts of mercury have built up in the environment, and emissions continue to be released from natural sources. Mahaffey acknowledges this, but says, "You have to start somewhere." She also believes the followup report by the Seychelles investigators, as well as the early information from the Faroe Islands, provides reinforcement for the EPA's position. "One thing we know about neurobehavioral testing is that the more subtle the effect, the harder it is to identify in younger children," said Mahaffey. "So it's our view that, until the data on older children are available . . . it's premature to assess the study." FDA officials, however, disagree with this conclusion.

The FDA supports an ongoing reevaluation of methylmercury levels, something Bolger says his agency has already been doing. With more data beginning to come out from the Seychelles and the Faroe Islands, Bolger cautions, "It's not the end of the story by a long shot." If both studies show central nervous system damage to children, Levin believes that's only half the research picture. The other half includes determining who's doing the polluting, and how much fish people are actually ingesting. "Right now the EPA is using long-range transport modeling to determine how far mercury carries once it leaves an industrial source," he said. According to Levin, "the EPA itself says these models are not that good. But they haven't had time to fine-tune their models. Part of the reason is they're under time pressure because of the lawsuits to get this information out. Now, with the delay, it would be a good time to do some field studies to validate the modeling they've been using, and then to go back and do source-specific analysis."

And while a lot of studies have been done on fish consumption, all of them, according to Levin, have flaws. "There [are] numbers on what's imported, what's purchased, but nothing solid on what's actually consumed. The EPA has relied on self-reported diaries from people in its fish-consuming surveys. So this is something that's amenable to further study," he said.

In response to all the criticism directed at the EPA report, Mahaffey simply says, "Facts are stubborn things. Methylmercury is a neurotoxin, and it's not going away."

Mark Wheeler